Power systems resilience: A comprehensive literature review

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Abstract:

Since most of the key infrastructure has become dependent on the constant allocation of electricity, it is supreme that the grid operates consistently daily and is more resilient in case of an unusual event. The concept of power system resilience (PSR) has been reviewed in different perspectives and to different extents. Being an emerging field, research and literature gaps are inevitable. The review suggests that significant gaps still exist, some of which have been addressed by this study. Therefore, this review aimed at understanding and evaluating the notions of PSR which comprise of definitions, properties, metrics, trapezoids and motivation. It further aimed at comparing different evaluation strategies using resilience frameworks. The study also considered PSR enhancement approaches to establish the classifications. It further aimed at analysing the impacts of hazards, including climate change on PSR and their adaptation measures. In view of this, article search, and literature review frameworks were built based on existing methods. Keywords were used to select articles pertinent to power system resilience. Step by step content search was used to review literature. The current literature gaps that were identified are presented, which shape the direction of future research in power systems resilience. PSR definition and properties that may be considered in drafting the standardized definition for PSR were proposed. Criteria for selecting quantitative PSR metrics is identified. PSR states, the capacities measured, and the activities undertaken for each of the event phase are developed. The resilience trapezoid which summarises concepts in literature and incorporates the long-term effects of climate change on power systems is proposed, as well as qualitative resilience assessment and enhancement framework. A 9-Step, comprehensive, closed loop PSR assessment and enhancement framework is also proposed. Finally, the paper further discusses the impacts of climate change on PSR and their associated mitigation measures.

Keywords:
Power system resilience, resilience frameworks, climate change adaptation, extreme events, resilience enhancement, resilience assessment

Word count: 9985

Highlights:

- Grid resilience definition and the factors that need to be considered in drawing a standardized power system resilience definition are proposed
- Resilience states, their respective measured capacities and resilience activities with respect to event period are analysed
- Impacts of climate change on power system resilience and their adaptation measures are presented
- Selection criteria for quantitative power system resilience metrics is suggested
- Powe system evaluation frameworks are compared, and a comprehensive framework is proposed
- Research gaps are identified

Abbreviations:

LPHI: Low probability high impact

CC: Climate change

Ref.: Reference

TNR: Transmission network configuration

CNT: complex network theory

HVDC: High voltage direct current

T & D: Transmission and distribution

PV: Photovoltaic

HDD: Hot degree days

CDD: Cold degree days

GCM: Global climate models

RCM: Regional climate models

RETs: Renewable energy technologies

RE: Renewable energy

PSR: Power system resilience

RT: Resilience trapezoid

PSRMs: Power system resilience metrics

DER: Distributed energy resources

RAPI: Rapidity

PI: Performance indicator

1.0 Introduction

Electricity manages lives, economies, and cities. Without it, lives would not only be inconvenienced, but could hypothetically be at risk [1]. A constant production and movement of electricity is therefore crucial to the functioning of the society. As much public attention has been spent on the production side of the power industry and resilience has only recently begun to capture the focus of a wider audience. Since most of the key infrastructure has become dependent on the constant allocation of electricity, it is supreme that the grid operates consistently daily and is more resilient in case of an unusual event [1]. The concept of resilience has been studied in various disciplines including, community, engineering, economic, ecology, and social [2]. Unlike reliability, resilience is characterized with low probability high impact (LPHI) events [3]–[6]. LPHI events are incidents that occur rarely but have severe impacts for example 300-year flood occurrence. One of the significant features of LPHI events that distinguish them from predictable power system failures is that power sources may not be accessible or available [7]. Consequently, to have a resilient system, the system under consideration ought to have a maximum diversity of supply sources and should avoid reliance on a limited set of power supplies. In addition, systems should be sufficiently flexible to react rapidly to events and to alter working processes even in short times [3]. Further, priorities for supplying diverse loads ought to be well-known [8]. The frequency and intensity of LPHI events has been increasing in the wake of climate change (CC), increasing population and economic growth [9]–[12]. [13] summarized the motivation behind generic resilience studies. Motivations for power resilience studies (PSR)include criticality of the grid system [3], [14]–[18], sustainable and economic reasons [3], [14], [15], vulnerability of the grid system [6], [15], [19], [20] and the increase in the frequency of severe weather events [20], [21]. The electricity grid is considered a “critical lifeline system” and “backbone of any modern society” [16]–[18] since all critical infrastructure depend on reliable supply of electricity and that network outages typically affect millions of people and present huge risks to everyday life, economic prosperity, and national security [3], [6], [14], [15], [19]. Authors in [6] indicated the vulnerability of reliable electric grids to extreme events. Frequent occurrence of natural disasters and malicious attacks has exerted unprecedented disturbances on power systems, accounting for the extensive attention paid to power system resilience [6], [19], which have unfavorable outcome on the economy [14]. The rise of power outages caused by extreme weather events and the frequency of extreme weather events has motivated the study of grid resilience [21]. There is also need to ensure that tools, methods, approaches and / or guidelines to resilience assessment and enhancement can be developed. The development of grid resilience assessment and enhancement tools, methods, approaches and / or guidelines is thus another cause for PSR studies.

Being an emerging field, studies in PSR are still in the infancy stage. The concept of resilience has been reviewed in different perspectives and to different extents. [22] presented approaches to security and cloud resilience related mechanisms. [23] reviewed the recent progress in the transmission network reconfiguration problems where complex theory theory-based indices for transmission were explained. The investigation and review of functions for improving power system resilience was reviewed by [24] in which enhancement methods for HVDC systems were explained. Conceptions of resilience, representative definitions of resilience by field and importance of testing resilience characteristics were reviewed by [25]. [5] presented statistical and simulation models in predicting natural disasters related to power system disturbances, strengthening, operations and restoration. Proactive resilience of power systems with a focus on extreme weather events was reviewed by [26]. The authors explained the use of microgrids and DER as enhancement tools for operational PSR. [27] focused on resilience of distribution system using a synchro phasor application where among others, resilience features were discussed. [28] reviewed classifications of suitable measures for managing PSR. They classified PSR based on time of event and provided main resilience features. They also discussed resilience-based planning for distribution and transmission systems. Approaches to resilience evaluation and quantification of PSR using different metrics was also discussed. [29] evaluated the methods for operation and control of networked microgrids. Existing approaches attending to microgrid cyber security was discussed by [30]. [31] presented an explicit investigation of empirical primary studies that address forensic incident response aspects of cyber-physical systems in smart cities. Prior reviews suggest that significant gaps still exist which call for further reviews. The contradicting definitions of PSR are yet to be reviewed. The criteria for selecting the PSR metrics is still silent in prior reviews, as well as contradicting resilience frameworks and resilience trapezoids. Furthermore, the resilience states, measured capacities associated with these states and their respective resilience activities are yet to be researched. The classifications of enhancement approaches used so far has also not been studied. Finally, further reviews never reported on the impacts of increasing climate change on PSR and their adaptation strategies. Therefore, this review aimed at understanding and evaluating the notions of PSR which comprise of definitions, properties, metrics, trapezoids and motivation. It further aimed at comparing different PS evaluation strategies using resilience frameworks. The study also considered power system resilience enhancement approaches to establish the classifications. It further aimed at analysing the impacts of hazards, including climate change on PSR and their adaptation measures. Following the above, this paper contributes the following:

1. Significant literature and research gaps which help in future research directions in power systems resilience.
2. Proposed frameworks:
    a. RT which summarises concepts in literature and incorporates the long-term effects of climate change on power systems

b. Qualitative resilience assessment and enhancement
c. A 9-Step, comprehensive, closed loop PSR assessment and enhancement

3. Definitions for grid resilience and the resilience trapezoid (RT).
4. Identification of the criteria for selecting quantitative PSR metrics
5. Comprehensive analysis of the following
    a. Selected PSR definitions which aids identification of properties that may be considered in drafting the standardized definition.
    b. Power system resilience states, the capacities measured, and the activities undertaken for each of the event phase.
    c. Applications of RT
    d. Impacts of climate change on PSR and their adaptation measures to enhance PSR

After the introduction, section 2 presents a standard review methodology. Sections 3 to 7 provide review results and discussions which are presented in distinct subsections namely, the notions of PSR, threats to PSR, metrics and quantification of PSR, PSR evaluation and enhancement. Section 8 presents the identified gaps and possible research directions while section 9 concludes the paper. Additional information which is relevant is included in the appendix.

2.0 Review methodology

Standard review methodology was used as adapted from [2]. Procedures were followed to, 1) identify articles, 2) review, compare and analyse the articles, and 3) identify current literature and research gaps. Frameworks were built to identify suitable articles based on [32], as presented in Appendix 1. The literature review was based on the aims and research questions. Specifically, the notions of PSR which comprise the definitions, types and general resilience concepts were reviewed, compared and analysed. In addition, the threats to PSR and their adaptation measures were also reviewed. Metrics of PSR, their definitions, classifications, attributes and selection criteria were targeted as well, in addition to PSR evaluation criteria. The study further analysed the different enhancement strategies, their classes, whether the concept of cost – benefit analysis was used and applications. This process is summarized in Figure 1.

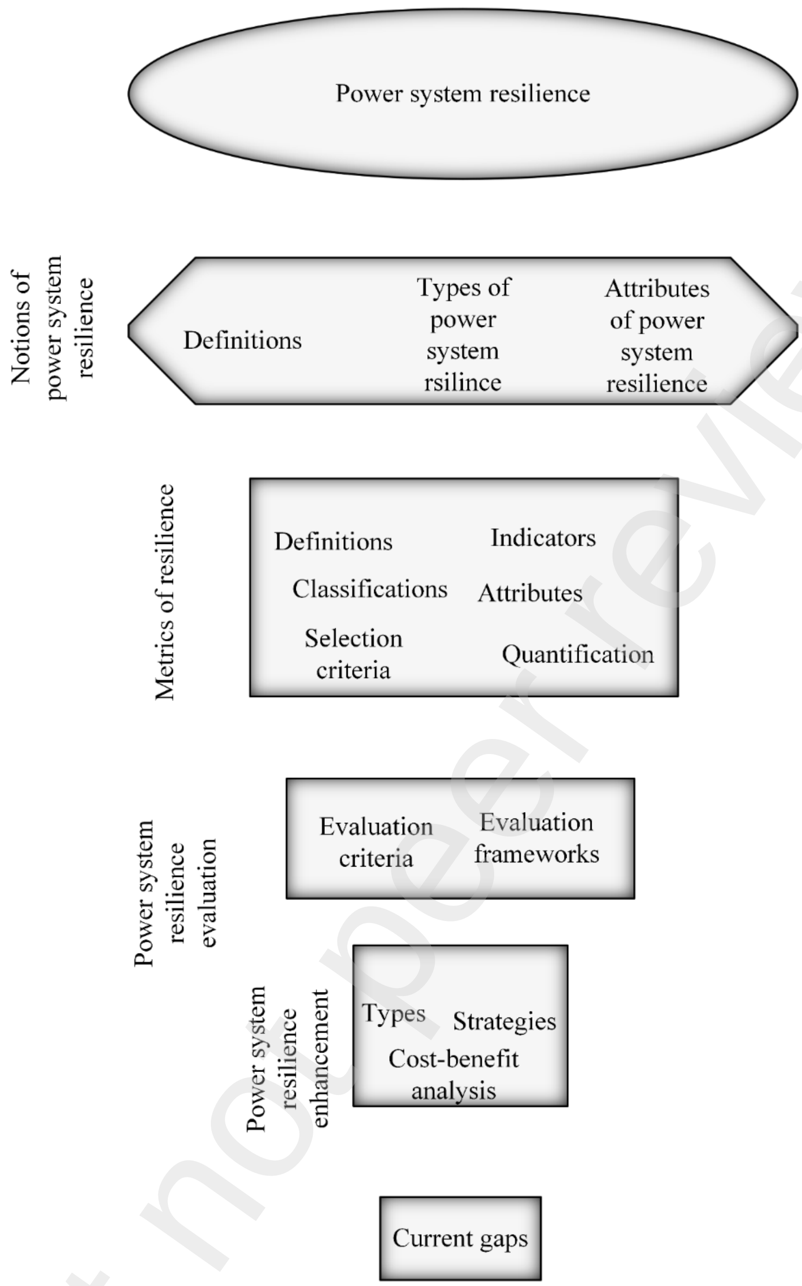

Figure 1. Power system resilience literature review methods. Redrawn. [Adapted from [2]]

Finally, the current gaps were identified. The identification of literature and research gaps was based on comparative analysis which was adapted from [33]. The definitions, classifications, concepts, RTs, evaluation frameworks, enhancement measures, were compared to establish diversities and potential gaps. Furthermore, explanation of how other assessments were carried out is explained.

After the generic literature review, a comparative analysis of the RTs and frameworks was performed. For the trapezoids, a comparison was made based on 1) naming, 2) number and description of resilience states and the associated resilience characteristics, 3) Y-axis (quantities of measure), 4) X-axis (disturbance progression), 5) initialization of measured quantity's degradation, 6) position of measured quantity after restoration activities. The woks of [6], [13], [17], [19], [28], [34]–[41] in Appendices (Table A.1) present these concepts. After compiling this, the outcomes and derived assumptions, concepts, applications and challenges or gaps were analysed. Similarly, for the frameworks, the comparison was based on 1) type of evaluation (qualitative or quantitative), 2) type of resilience activity (assessment or enhancement or both), 3) 1st stage of framework, 4) mono- or multi-hazard assessment, and 4) existence of preparedness assessment. The choice of components to be compared was based on the preliminary review regarding the concepts of PSR. This comparative framework analysis was based on the works of [6], [7], [9], [13], [19], [21], [37], [42]–[47]. In investigating the enhancement measures studied, the works of [3], [14], [16], [20], [46], [48]–[60] were reviewed based on type of enhancement studied, consideration for cost-benefit of the enhancement measures and if combination of different classes of measures (e.g., operational and structural) was used by the authors. The results of reviews, comparisons, analysis and identified gaps are presented in respective sections under Sections 3, 4, 5, 6 and 7. In the tables of results, (Table 3 and Table 4) S stands for structural, Op for operational, and a dash means no consideration by the authors.

3.0 The notions of power system resilience

3.1 Defining PSR

The definitions present a resilience theory, which is believed to be classified into two groups, static and dynamic [44]. While static resilience determines the operation of a system post an interruption, along with its autonomy of time, a dynamic resilience explores how rapidly a system regains its standard operation. [38] suggested that resilience definitions should depend on the identification of resilience domains, which are classified as economic, engineering, organizational and social. The definition of resilience of the power system is derived from definitions provided by other disciplines [21]. The standardization of grid resilience definition is vital and recommended, as a foundation for supplementary studies. Different authors in [6], [7], [10], [13], [15], [16], [18]–[20], [35], [39]–[41], [49], [61]–[68] presented a range of PSR definitions. Having reviewed the range of definitions as in Appendix 3, the proposed grid resilience definition is the ability of an interconnected network of different components, institutions, and grid operators to adequately plan and prepare for resilience, avoid / prevent adverse impacts of hazards. In doing so this will minimize the impact of threats and related disasters, restore the system quickly, and improve where appropriate, reduce disaster risk factors and reduce vulnerability of the grid system against actual or expected impacts of hazards, in a cost-effective way where benefits of enhancing the grid are either quantifiable or non-quantifiable. This definition considers planning as a key factor. The significant roles played by the grid operator, development agents and the entire electricity sector cannot be overemphasized in guaranteeing grid resilience. Based on the diversity of PSR definitions, the following properties were identified and are recommended to be incorporated in the development of a standard definition.

1. Power system ability
2. Maintenance of electricity supply
3. Sustainability of social services
4. Extent, type, severity, and duration of event / potential event
5. Limitation of impact / loss
6. Extent / degree of preparation, anticipation, adaptation, resistance, response, absorption, degradation, and transformation
7. Rapid power system recovery
8. Acceptable level of loss / impact, recovery time and recovery costs
9. Continued operation in damaged states
10. Dynamic resilience

3.2 Types of Grid Resilience

[39] classified power systems resilience into operational and infrastructure, with operational resilience being the ability of the grid to maintain operational strength and sturdiness and infrastructure resilience being the physical strength of a power system for minimizing the portion of the system that is ravaged, disintegrated or in general becomes nonfunctional. In [69], resilience based on either planning or operation domain is suggested. Planning resilience encompasses the pre-event resilience as opposed to operating resilience which considers how resilient the power system can be during an event. However, [18] referred to this classification as resilient enhancement strategies. The planning phase is most important because it determines system preparedness and response in the wake of hazards. [70] classified resilience into either infrastructure, operational or organizational. The works of [71] and [70] were used to classify grid resilience in terms of infrastructure, operational and organizational in this paper, where organization domain could stand for either regulator, operator, utility, or customer.

3.3 The Concept of PSR

The concept of resilience is based on the "bounce back" principle [72]. A resilient grid is considered as an interconnected network of different components [62], [73] that has four fundamental properties of resilience, namely anticipation (outright avoidance / resistance / repulsion of adverse impacts of hazards / being able to prevent possible damage), absorption (capacity to minimize / mitigate / lessen / limit the adverse impacts of hazards / threats and related disasters), recovery (restoration and improvement where appropriate, of disaster affected systems, and communities, including efforts to reduce disaster risk factors), and adaptability (initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected impacts of hazards by studying the previous events and improving or advancing the systems' capacities) after the damaging events [20]. Consequently, [72] perceived resilience as the adaptive ability of enhancing performance, owing to knowledge and alteration, learnt by unceasing change.

According to [21], the easiest means to state grid resilience is through examination of the overall impact, which is the area of the grid resilience triangle. This concept was adopted and modified by [74] who believed that resilience triangle is founded on the reflection that disturbing events cause sudden fluctuations in the performance quality, and steady recapture to the original performance quality level. Any resilience improvement approach endeavors to maximize this area under the curve or minimizing the triangle [20], [75].

Resilient triangles leave behind the degraded state hence they are not an ideal approach to estimate the impact. The frequency and degree of performance descent when a disturbing event attacks, duration that the system stays in a ruined state, and frequency of recovery to pre-disturbance condition are described by the RT [49], which is discussed in the next section.

3.3.1 The RT

Different researchers have presented different RT [6], [17], [19], [28], [35]–[41], [76] , which depict diversity in resilience concepts. An early version of RT in power systems is presented in [36], where steady system operation before an event strike is assumed, and that it will go back to its original state once the event is over. This assumption was also observed in [6], [17], [19], [35], [37], [39]–[41], [76]. After an event, however, the power system might have either a decreased capacity [28], [36], [38] or go back to initial capacity, be completely degraded, or have an increased capacity (transformation) [77].

Another assumption derived from the diversity of RT is that the system starts degrading immediately after the event initiation except in [34]. Depending on the type and extent of event, the power systems may take time before degradation starts. It is further assumed that the system functionality is not subjected to any disturbing event prior to the main event but the long-term impacts of climate change on power system operation and hence resilience cannot be overemphasized. [76] demonstrated the impact of CC in a RT.

CC slowly reduces the normal performance of the grid which exposes the grid to severe impacts in the event of serious weather events. Sometimes the power system might fail even without a LPHI event. This is especially the case with systems that have limited routine maintenance and aged. Mitigating CC might have a positive impact and possibly lessen the rate and magnitude of degradation when LPHI event strikes. The diverse application of RT is also noted. For example, [36] referred to the trapezoid as a performance curve because it is used to demonstrate the performance of the power system under a LPHI event. A RT can therefore be considered as a performance curve [36], resilience curve associated with a LPHI event [17], system performance and state transition indicator [38], illustrative process of changes in the performance level of a resilient power system [9], [25], resilience process scenarios and capacities indicator [77], disturbance and impact resilience evaluation curve [2], linear approximator of system performance [41] and system status curve [8]. These RTs also demonstrate 1) how the performance changes with respect to the state of disruption and time [38], 2) availability of security margins [40] where deeper impacts mean inadequate security margins, 3) whether or not the power system will be able to supply critical loads under disturbance [35]. RT review suggested the resilience concepts that can be extracted as discussed in the next section.

3.3.2 Trapezoid-based resilience concept

Another critical concept that can be depicted from the different RT is the phase transition of a power system before an event to when the restoration procedures are completed. The phase description, and the respective measured resilience capacities and resilience activities are derived and summarized in Table 1.

Table 1. Trapezoid-based resilience concepts

Period	State description	Measured resilience capacities	Resilience activities
Pre-event	Preparedness [19], [28] , normal [6], [34], [40], resilient [11], [35], [39], , preventive and anticipation [19], [36], [37], avoidance [41], stable [38]	Robustness, resistance, preparation, reliability [35] [37]	Forecasting, prevention, boosting pre-disturbance resilience, estimation, prepositioning of the resources, monitoring [21] [39]
Immediately after event initiation	Damage propagation [48], event progression [9], [35], vulnerable, disturbance progression [11], [39] resistance [6], [19], [28], [34], [35], emergency [40], survival [41], absorption [77], system disruption [38]	Vulnerability, resistance, rate of degradation, magnitude of degradation [35], [38]	Manifestations of hazards, performance standards diversions, degradation, resistance, coping, functionality reduction, remedial working elasticity, alleviating slope/speed of resilience degradation, duration of damaged state minimization, emergency, and remedial measures [39]
Event stops but before restoration	Adaptation [77], assessment [34], disrupted [38], response [19], [28], [35], degraded [6], [9], [11], [34], [35], [39], recovery [41], in extremis [40]	System agility, brittleness / fragility, redundancy, adaptive capacity, resourcefulness [9], [19], [35], [38]	Observation, resource mobilization, emergency response
Immediately after restoration starts	Recovery [19], [28], [35], [38], [41], [77], restoration [6], [9], [11], [34], [40]	System response, recovery rate, system recovery [9], [35], [38]	Restoration, repair, scraping off [5], [6], [21], [39], [49]
When restoration ends	Post restoration [9], [11], [39], stable / recovered [38] normal [6], [34], [40], transformation [77], ultimate operation mode [23]	Robustness, resistance, adaptation / adaptive capacity, system capacity [35], [37]	Event assessment, grid flaw detection, long improvement approach formulation, planning resilience, resilience policy reviews, capacity building, formulation of guidelines, cost-benefit analysis [19], [20], [49]

Applications of RT in measuring different resilience quantities is also identified. Quantities such as grid functionality [38], performance level [34], [35], [39], resilience level [77], resilience indicator [11], system function [21], power system status [6], [34], performance index [41], resilience [6] [29] [52], system performance [28], and overall performance are all used as quantities of measure by these trapezoids. These can be grouped to define a PSR trapezoid as a figure that defines the resilience levels of power systems with respect to time.

The RT further summarises the main phases of the resilience cycle, which are shown in Figure 2, as a summarized climate effects-based trapezoid, from where the following are noted:

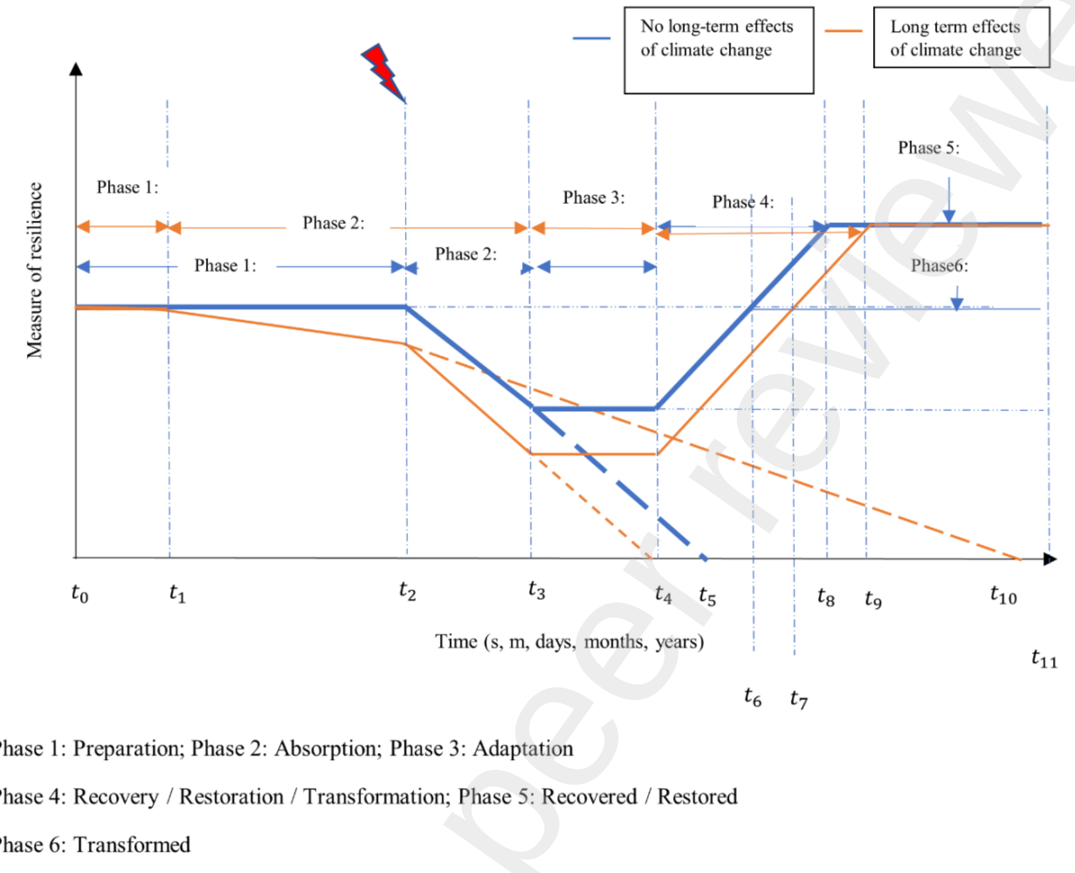

Figure 2. Summarised climate effects-based RT

- For the same magnitude and duration of impact, unlike the system that is not subjected to long term impacts of CC, the system exposed to long term effects of CC will
  - Be less resilient as evidenced by the decrease in area under the trapezoid
  - Experience more impact, for example, more decreased performance levels
  - Take longer time to be restored (t_7) to their initial state
  - Take less time to completely fail
  - Takes longer to be transformed
- Resilience planning must be undertaken before the systems start experiencing reduced functionality. The preparation stage in systems exposed to long term effects of CC might be shorter ($t_1 - t_0$) than the other systems ($t_2 - t_0$)
- Absorption phase for systems exposed to CC impacts does not wait for LPHI event to strike ($t_3 - t_1$) unlike the supposed normal system ($t_3 - t_2$)

- Depending on the nature of disturbance, time under consideration can be in seconds, minutes, days, weeks, months, and years.
- It is possible for the power system to fail straight from the effects of CC without necessarily being exposed to other LPHI events especially for aged and unmaintained systems.

4.0 Threats to PSR

The following questions were answered in this section. What are the impacts of CC and extreme weather events on PSR? How does electricity demand become a potential threat to PSR? What adaptation measures have been put in place so far to address PSR issues?

4.1 CC, extreme events and PSR

Studies indicate that CC is responsible for the increase in frequency, duration, and intensity of extreme weather events [9]–[12]. CC is also responsible for rising global temperatures, changes in rainfall patterns, elevated occurrence and strength of drought days, cloudiness, higher winds, sea-level rise [9], [10], [12], [78]–[83], cold waves, heavy snow and lightning strikes on or near overhead conductors [84]. Each of these impacts of CC can affect the power system in different ways, at different degrees either on their own or in combination as is usually the case. The degree of damage on the power system depends on the significance of the weather or climatic conditions, and the condition of the components. Prior works have focused on the impact of extreme weather events (as another effect of impact of CC) on power systems along with their mitigation strategies. This multitude of studies in this direction owes to the fact that LPHI events are among the top causes of cascading outages and severe impacts following a disruption. However, CC is here to stay, and world trends indicate the possible increase in CC [83]. This calls for consideration of climate adaptation and mitigation. Power systems operation (as opposed to planning) has always been closely interlinked with weather conditions and susceptible to extreme weather events that may in some cases be a large, if not the largest, contingency event. It is useful to clarify that the "CC impacts" relate solely to how this interdependence and susceptibility are likely to change over the years. The critical issue arising from CC is that these natural hazards are projected to intensify, become more frequent, and become more unpredictable. It was thus important to consider CC in the system resilience studies.

The impacts of CC on generation, transmission, and distribution (T&D) and demand are reviewed in [84], [85]. Rising global temperatures affect solar PV modules, hydropower generation, T&D, and demand landscape. Higher ambient temperatures reduce the generation efficiency of solar PV modules [10]. The conversion efficiency of the PV modules is negatively affected by the elevated temperatures which reduce their optimal output. Elevated temperatures also affect generation output of hydropower plants due to increased evaporation in water bodies [10], [85]. Rising temperatures further affect the T&D system in terms of transmission efficiency and capacity. Physical characteristics of different power system components including transformers and overhead lines have linear relationship with allowable maximum operating temperature. Increasing global temperatures accelerate T&D losses and line sag [83], lower existing capability and derates T&D equipment to survive the elected temperatures [10]. Further, the demand landscape is affected with the rise in global temperatures due to increase in cooling and irrigation needs. [36] [59] established that increase in global temperatures affects the insulation of the overhead lines which reduces the ability of the transmission lines to deliver power at their rated capacity. More studies need to be conducted in the case of certainty in demand increase coupled with increasing CC. Changes in rainfall patterns and elevated occurrence and strength of drought days could negatively influence hydropower generation and impact water disposal for cooling in thermal and nuclear power plants [83]. Floods damage the screens at the hydropower plants intake points as well as decreasing the head due to flooding of the tailrace. Increased rainfall patterns affect the generation, T&D, and the recovery process in the event of floods where transport networks are also affected. Increased precipitation also affects the recovery time and process if the precipitation is too excess to permit maintenance works. There are physical risks in terms of damage of T&D and generation equipment due to floods for example [83]. Elevated occurrence and strength of drought days significantly reduces the generation potential of the hydropower plants. In addition, there is also significant increase in demand following increases in irrigation needs. Electricity generation of solar PV power plants is not only affected by the rising ambient temperatures but also by the extended projected cloudiness [9]. Extended cloudiness is a potential grid resilience risk especially when the solar PV power plants are integrated to the main grid as these further increase the grid instability. Higher winds affect both the power generation and delivery infrastructures. Wind turbines are expected to work within a certain speed range. Too high a speed not only affects the output but also the physical structures in the form of breakage. T&D structures are vulnerable to very high wind speeds because some of the weaker structures can be brought down. In excessive windstorms, even solar PV panels can be destroyed. Sea-level rise on the other hand, affects the generation (compromised output, physical risks, and inhibition to new asset development)

T&D (physical risks and inhibition to new asset development) and demand (water supply) as well.

There is still ongoing research to curb the effects of CC on critical infrastructures. [83] put up a framework for risk measurement and enhancing the resilience of critical infrastructures centred upon the ideologies of elasticity, variety, and industrialised ecology, incorporating both short-term and long-term influences of climate consequence. Risk assessment is considered one of the critical activities to be undertaken in the prediction stage as a positive step towards climate risk resilience. CC mitigation and adaptation might have a positive impact and possibly lessen the slope or rate of degradation when LPHI event finally strikes. These studies are important as they provide the planners with the rate at which the power system is slowly degrading. Climate conditions affect many components of the power sector, and these effects are two-fold, to the power sector and to the consumer. These disturbances, in turn, negatively affect life-threatening services and facilities. Knowledge of threats to the power sector is a vital stage in forecasting a robust power system. Natural disasters vary widely and are location specific. In [3], [4], conventional hazards to PS were categorized into natural, geological, and accidental. [69] classified LPHI events as either natural or man-made. Table 2 presents a proposed classification of power system threats.

Table 2. Classification of power system disasters

Natural Disasters		Accidental Disasters	
Climatic	Geological	Technological	Human-centered
Cyclones	Earthquakes	Infrastructure failure (due to natural wear and tear)	Accidents
Floods	Volcanic eruptions	Poor workmanship or design	Terrorism
Drought	Tsunamis	Unpredictable loads	Cyber attacks
Wildfire	Landslides	Water-line disruption impacting power sector	Political disruption
Wildlife interactions			Thefts
Solar flares			Explosions
Tornadoes			Bombings
Lightening			Poor planning
Heatwaves			Mindset

4.2 CC, electricity and PSR

Many studies in CC assess its impacts on demand profile. Generally, CC will increase average annual electricity demand [86]–[98]. [86] demonstrated that in the wake of extreme temperatures, electricity utilisation escalates more with heating demands than with cooling demands in Portugal. This was explained by adoption of other smaller cooling technologies. In contrast, [87], [88] proved that the escalated need for cooling would lead to the increased electricity utilization in China, which is explained by China's climatic warming trend. This was also observed for Northern and Southern Europe [90]. This is because climate change will shift the distribution of the seasonal electricity consumption [89], [92]. At minimum temperatures, temperature surges incipiently effectuate decrement in electric space heating and to a certain degree a decrease in the utilization of indoor appliances, the use of which escalates during cooler weather [91]. At elevated temperatures, the effects of space cooling through air conditioners and the uses of other appliances prevail. While climate warming reduces electricity consumption for heating in winter and escalates electricity consumption for cooling in summer, it conclusively escalates consumption [89], [94]. Uncertainty in population, tariffs and climate change was investigated in [93] where each one of the electricity demand determinants was let to alter whereas the rest of the factors were held constant. Results suggested that the impact of the weather variables to the general path of electricity demand is relatively moderate, but positive over the full projection time. Generally, electricity demand due to climate change has shown to escalate during summer and spring times [81], [89], [94]–[98]. This is explained by an increase in the quantity of buildings, the portion of connected air conditioners (ACs), and the extra cooling load on those air conditioners. This is attributed to the different heating and cooling methods in different regions for example in China [97], [98]. In northern China, the heating energy is primarily obtained from coal and natural gas and the refrigeration energy is obtained from electric equipment for example air conditioning. Thus, the electricity demand is higher for cooling than for heating. Other researchers suggest that CC will likely affect the peak electricity demand more than the average annual demand [96], [99]. In [81], the vulnerability of ratings of overhead lines due to high temperatures was reported. Higher temperatures reduce the current carrying capacity which consequently raises electricity demand. Installation of higher temperature novel conductors was proposed as a mitigation. Increasing distributed energy resources as opposed to transmission lines is also a comparable mitigation measure. Authors in [99] argued that changes in electricity demand have numerous impacts on power system planning and operations. Electricity demand changes also affect PSR entirely, either in planning, operational and infrastructural resilience in form of resilience costs in resilience planning, operation, and infrastructure improvement.

4.3 Adaptation measures against CC and its impacts

Adaptation works on coping principles. CC adaptation was defined by [100] as a means to cope with CC impacts. Adaptability studies target enhancement of strategic resilient elements to assist thwart the impact of *future* climatic events [17]. These studies further boost sturdiness, resourcefulness, and recuperation before an imminent disaster. The improve in resilience for the energy sector can be at both large-scale and household level.

[9] classified the forms of climate adaptation strategies into (1) structural, which was further subdivided into technological, engineering, and eco-system based, (2) capacity building, which was further classified into educational, informational, or behavioral adaptation and (3) institutional, which is further categorised into economic tools, laws and regulations and governance. Adaptation strategies for a single classic event or multiple events fall into either one or a combination of two or more of all of the forms. The relationship between CC adaptation and resilience was also observed in [101], where it was perceived that principles of resilience were inherent in CC adaptation strategies and that different forms of adaptation strategies build resilience.

Most CC adaptation studies focus on other resilience disciplines. There has been limited research on these studies with respect to PSR. CC adaptation measures were classified by [101] as (1) hardening (structural) which might comprise undergrounding power delivery structures, upgrading, re-routing, elevating structures or having redundant structures, and (2) effective operating procedures [17]. The structural adaptation measures aim at lessening the exposure of power system to impacts of CC while effective operating procedures aim at minimising the restoration time which improve the recovery features of resilience. Microgrids and DERs were considered as a means of building PSR against the impacts of CC in [17], which was done to enhance operational capability. Geothermal energy was used as a climate adaptation strategy in [102] where a double relationship was observed. On the one hand, there was maladaptation which takes place if geothermal resources were not properly or sustainably implemented. On another hand, there was adaptation which was achieved through sustainable water heating, electricity generation, sustainable livelihoods, and eradication of effects of drought in hydropower. RETs like biogas, improved cookstoves, micro hydro and solar power were also recommended by [103] as a way of rural adaptation to CC as these reduce not only traditional biomass use but also carbon dioxide emissions. Policy and regulatory instruments in solar energy were acknowledged by [100] as adaptation measures in power systems, which can be applied either at enterprise, regional, national, or international level. At an enterprise level, policy could specify the amount of energy to be generated. The adaptation of thermal power plants was studied in [104], where among other measures, relocation of power plants and soft measures like zoning and improved building codes were suggested. The optimal orientation of coal stockpiles which were vulnerable to precipitation, wind and temperature variations were also suggested in addition to the use and renewal of standards for construction., The installation of flood control measures, dry cooling towers and factory water recycling to promote cooling, lightning protection, and rerouting cables to underground were also considered as adaptation measures against the impacts of CC. Most researchers consider capacity expansion as a CC adaptation measure in power systems. These expansions can be in form of either DER or peak load shifting [96], which help in preventing substations from overloading. The capacity mix [105], which must result in desired electricity mix and corresponding costs of climate resilient energy systems while ensuring that the electrification, CC mitigation and adaptation goals are achieved, was also proposed. Further, rescheduling investments, investing more in carbon management technologies and RE plants to compensate for the uncertainty in hydropower generation, policy and gas prices were suggested in [106]. Ref. [107] recommended (1) deployment of "soft" infrastructure adaptation which were small-scale, less capital intensive but enhanced infrastructural (physical) resilience, (2), training policy makers as a way of promoting institutional resilience and (3) education and awareness to achieve community resilience to impacts of CC. Power systems suffer from either physical, institutional or community level challenges under CC hence, the proposed adaptation strategies.

5.0 Metrics and Quantification of Resilience

5.1 Metrics of resilience – definition, classification, attributes, and the selection criteria

The words metrics, index, indicator, functionality were used interchangeably [69]. Technically, a metric is a system or standard of measurement. An indicator (index, measure, gauge, mark, sign, or signal), on the other hand, is anything that indicates the state or level of something. It is a guide to a metric (standard, yardstick, benchmark, or criterion). The PSR metrics (PsysRMs) are tools to measure (quantify / assess / evaluate / calculate / determine) the resilience level of a power system [69].

[69] proposed a metric framework system which classifies the PSR metrics into performance and non-performance based. Performance based metrics were further categorised as either performance or consequence, which can either be specific or general. Specific performance metrics measure the direct output of the power system including power, duration, frequency, probability, and curve as opposed to consequence-based metrics that measure the impact of the power system or grid on various structures like economics, social, geographic, and safety and health. While [71] categorised the PSRMs as either operational or infrastructural resilience, [35] classified PSR metrics into four; metrics based on resilience features, metrics based on reliability properties [16], code-based metrics [108] and other metrics. On the contrary, [42] generalized these metrics into either flow- or centrality-based metrics.

The measurement of resilience in power systems is an emerging field, with several proposed resilience metrics, such as the resilience triangle and trapezoid, with the trapezoid being the most used and accepted metric [20] [35]. Some authors consider the resilience curves as one way of defining PSR [39]. Presently, there is no universal standard assessment methodology nor metrics for PSR assessment. [6] recommended that quantitative indicators ought to first be clear and designed to define features' components [69], in addition to being quantifiable, repeatable, and comparable [10] [11]. Further, quantitative resilience metrics should be time dependent [35], [73], to secure the performance [16] of the network during the different phases associated with an event [39] and should also be able to reflect the consequence of a certain disruptive event or the effectiveness of the resilience measures [16]. [3] further expressed the need to describe a quantity that was typical of the practical abilities of the grid in terms of the quantity and / or quality of the services provided by the grid. Metrics should also consider uncertainty [2] [16], and should be helpful in making planning, operation, and policy-making decisions [2] [16], risk-centred [10], able to distinguish operational resilience from infrastructure resilience [69].

It is challenging to come up with the metrics because the process is not standardised. Prior studies have hinted on the selection criteria for PSR metrics. These are summarised as: aim of the resilience study [109], inherent uncertainty in the grid [10], policy directives [10], functional capabilities of the power system [3], expected degree damage of the system, risk of system splitting and generation and transmission margins [9], extreme event phases [42] and critical infrastructure [71], RT [42] and class of systems [110].

5.2 Quantification of Resilience: The metrics

Apart from the impact assessment, some quantitative indices can be added to measure the power system resilience. [6] worked on a distinctive Performance Index (PI) of the power system in terms of time and the incident of a severe disruption, where the time before the event can be well thought-out as a quantitative gauge to describe the class of the prevention period. This period can also be used as a qualitative gauge to define the status of preparation from a qualitative point of view. Different system parameters can be used to define PI, for example energy not supplied [109], energy generated, number of customers without power or number of transmission structures affected. [1] suggested a percentage of utility infrastructures disrupted by extreme events, segregated into overhead and underground systems, percentage of customers without power and outage duration, and percentage of critical facilities without power and the outage duration as the system's performance indicators. The segregation into which type of infrastructure suffers the most impact helps to properly focus on appropriate and optimal resilience enhancement solutions.

[109] presented power system resilience metrics (unsupplied energy) that can be used to quantify the resilience characteristics. The metric, however, failed to capture the rate at which the power system degrades or recovers. Restoration time is also an indicator that pronounces the restoration process's quality after a precise disruption [6]. The shorter the restoration time, the resilient is the system. It remains a challenge to decide how short this restoration time should be. Different systems should have different standards according to system capacities. The restoration index must be compared against the standard. Shorter restoration times significantly reduce the magnitude of impact. [10] introduced a PSRM framework and methodology to compare resilience improvements, the cost-benefit of improvements, and a method to de-rate the resilience of the system due to uncertainty within its elements (e.g., DERs). This framework incorporates the control systems resilience framework and the RT presented in other works and the resilience threshold. The resilience threshold marks the maximum acceptable level of degradation. The performance metric used to set this threshold in power systems could be amount of load loss [111], retention of critical loads (such as hospital and emergency response), available spinning reserves, frequency nadir or other regulatory requirements. [10] suggested an area metric which describes the adaptive toughness of a system. In [16], a PSRM that incorporates the resilience capabilities and the time to recover was reported. While these newly proposed metrics are not yet widely applied in the power system, traditional reliability evaluation metrics are still in use. Comparability is not easy

because different researchers might have different levels to interpret the immediacy of the disturbance strike. [112] introduced four indices to quantify resilience from different dimensions. They quantified the expected number of power lines that will be lost following a damaging event. They also modified prior works to suggest two reliability indices, unserved expected demand, and probability of load loss. The proportion of ''recovery'' to ''loss'' suffered by a system describes another type of resilience indices according to [8]. The higher the proportion, the greater is the impact because it means more resources are required to restore the disturbed system to its pre-disturbed state. It must be noted that this might not always be the case especially in areas where damage is significantly a factor of poor infrastructures and not necessarily high magnitude of damaging event. [3] recorded a measure of elasticity that computes the elasticity of a system to a set of N events where the resilience indicator is a function of time, a figure of merit, and the stress induced by the events. This metric is particularly important because power systems are exposed to more than one event. [113] proposed resilience indicators from a power system and component level scale. Their work covers the gap left by other works on solving a particular failure mode. From the power system perspective, the overall system resilience indicator considers the probability of the failure scenarios, the original performance decreases due to scenario and a set of possible failure scenarios. From the component perspective, the authors proposed component resilience indices based on event phase, before and after the event strikes. It is critical to measure the resilience of the components prior to an event as this gives direction to weak points which become vulnerable to extreme events. [74] considered Rapidity (RAPI) to recognize the absorptive and adaptive ability. This is the average gradient of the resilience indicator. In the absorption phase, RAPI defines the rate at which system degrades following an extreme event. In the recovery phase, the steeper the gradient is, the faster is the recovery rate and the minimal is the RT area. In the transformation phase higher gradients signifies faster rate of capacity increment. This is analogous to what [39] discussed as the ΦΛΕΠ resilience metric system. During disturbance progression, Φ indicates how quickly the resilience falls (slope of the degradation phase), Λ indicates how low the resilience falls (the extent of the impact). In the post disturbance degraded state, Ε indicates duration of the degraded state. in the restorative phase, Π indicates the speed of recovery (the slope of the recovery phase). These four metrics were used by [39] to define a 5th metric, the area of the trapezoid. To quantify the ΦΛΕΠ metric, authors used the amount of generation capacity and load demand that are connected and available for power generation and consumption respectively, as indicators for the operational resilience; and the number of online transmission lines is used as an indicator for the infrastructure resilience. Other quantities that were used as indicators in different literature were: unserved energy [5], [10], operating cost and load loss [114], power supplied to critical loads weighted by their criticality [8], total load served [75], system load percentage of transmission line online [6], loss of load frequency, loss of load expectation, expected energy not supplied, mismatch between dispatched power and actual power generated at a specific time, and severity risk index [111], time-to-recover [3], amount of loss incurred by the system and metrics to reflect the toughness of power system (the expected damage degree of system, the risk of system splitting, and the generation and transmission margins) [9].

6.0 PSR Evaluation Criteria and Frameworks

Numerous frameworks for enhancing resilience assessment have been built and implemented in literature, which are categorized as either qualitative or quantitative frameworks [7] [16] [18] and [115]. PSR assessment can also be based on either the impact it experiences due to a LPHI event or the grid capability it possesses [11]. The impact and the grid capability can be assessed through the grid conditions during the occurrence of LPHI event.

6.1 Qualitative resilience evaluation

Qualitative resilience evaluation is where different attributes and resilience abilities can be considered at the same time [7]. The attributes considered in the qualitative evaluation usually include the power system and other interdependent systems, such as information system, and fuel supply chain. Abilities include preparedness, mitigation, response, and recovery, e.g., the existence of an emergency plan, personnel training, and repair crew availability [7]. Prior studies have considered different aspects but mainly, frameworks are main outputs of the qualitative resilience studies [3]. These qualitative frameworks can serve as a guidance for long-term energy policy making, as they provide a generally thorough picture of the system. Measurement of adaptive capability and notions of diversity, redundancy, system configuration and observing are reported as some of the frequent ideas to measure qualitative resilience, irrespective of the field [3]. Affordability, availability, accessibility, and acceptability are also attributes of resilience which demonstrate the ability of a system to plan/prepare, absorb, recover, and adapt to external disturbances [3]. Authors in [116] presented qualitative measurement of resilience at systems, asset and community / regional level. They used checklists and questionnaires. In [117], organisations' vulnerability matrices were developed to establish common issues that create barriers to enhanced resilience. Multi-dimensional energy resilience metrics were presented in [118], which are key in implementation guidance for energy related planning, design, investment and operation. Metrics scoring was used to measure resilience. In [119], a disaster resilience index for coastal communities at a local level was proposed. An AHP approach was used where goals, assessment criteria based on resilience components and then attribute elements were used to assess the index. Qualitative resilience is usually reported as either low, moderate, high or very high [117]. Qualitative enhancement measures are those that enrich preparedness and minimize recovery or restoration time such as resource mobilization, development of guidelines, policies and plans in addition to capacity building. The review of resilience evaluation by prior studies (Table 3) suggests that qualitative resilience assessment in power systems has not been given much attention. In Table 3, the dashes mean no consideration by the authors.

Table 3. Comparative analysis of power systems resilience frameworks

	Type of evaluation		Resilience activity			
Ref.	**Qualitative**	**Quantitative**	**Assessment**	**Enhancement**	**1st stage of framework**	**Preparedness**
[6]	-	✓	✓	-	event modelling	-
[7]	-	✓	✓	-	resilient goals' definition	-
[9], [42]	-	✓	✓	✓	weather model	-
[13]	-	✓	✓	✓	resilience goals' definition	-
[19]	-	✓	✓	-	event modelling / threat characterisation	-
[21]	-	✓	✓	✓	event & grid modelling	-
[37]	-	✓		✓	vulnerability studies	-
[41]	-	✓	✓	✓	metrics definition	-
[44]	-	✓	✓	-	event modelling / threat characterisation	-
[45]	-	✓	✓	✓	threat characterisation	-
[46]	-	✓	✓	✓	event characterisation	-
[47]	-	✓	✓	-	threat characterisation	-

In addition, preparedness, which is key in resilience management, is yet to be assessed. Prior works were used to propose a qualitative resilience assessment and enhancement framework in Figure 3. This framework is a combination of prior works assessment methods and the authors’ opinions. Monitoring is critical in ensuring that measures are being used.

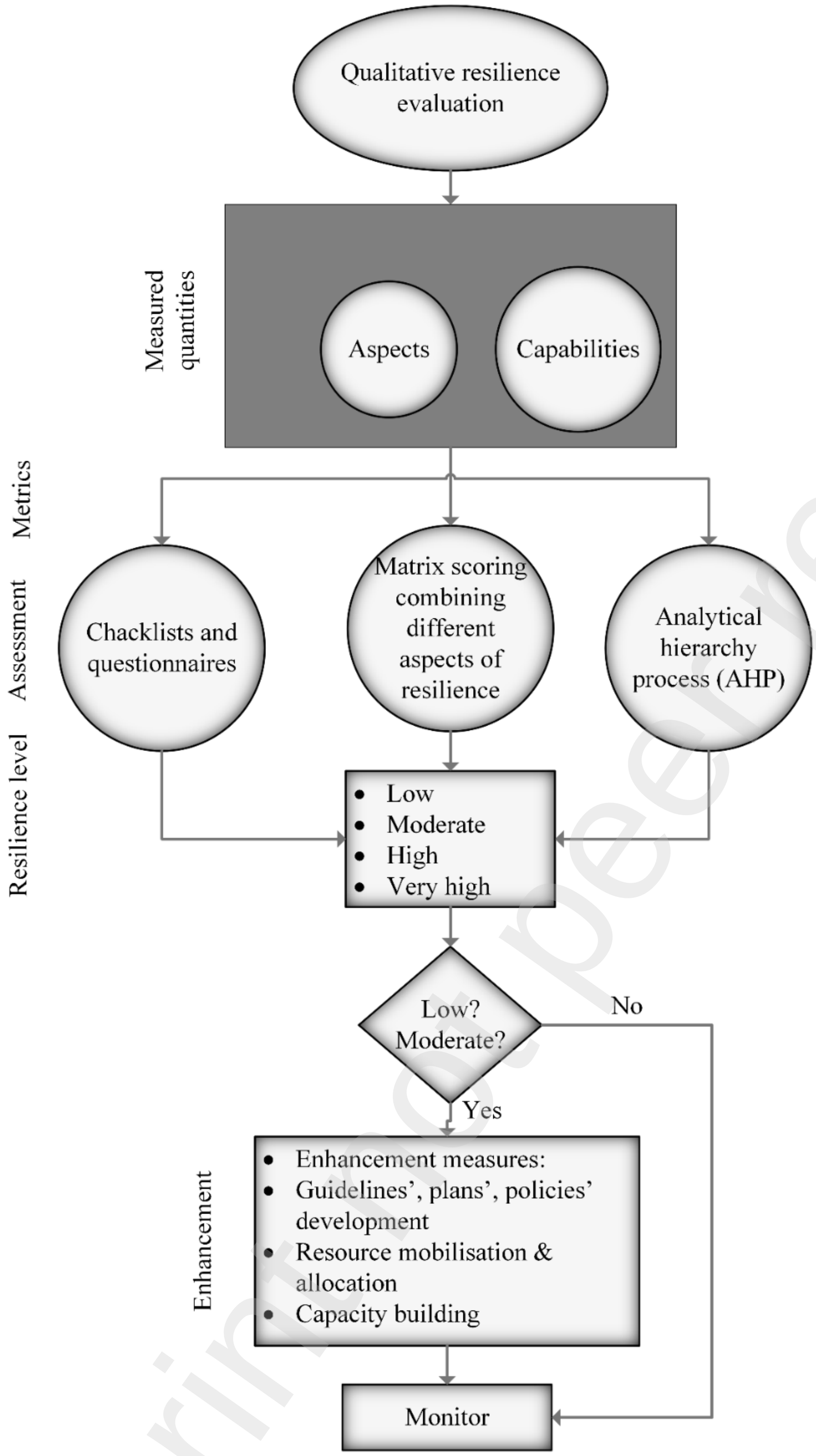

Figure 3. Qualitative resilience evaluation. Adapted from: [7], [117], [118], [120]

6.2 Quantitative resilience evaluation

Quantitative resilience evaluation has been frequently centered on the quantification of system performances. Quantitative metrics remain informative when assessing the efficiency of resilience actions or comparing the degree of resilience of distinct structures [7] and in preparing and managing appropriate enhancement strategies [11]. Resilience is quantitatively reflected in the reduced magnitude and duration of deviation from the targeted performance. Most quantitative evaluations are based on single traumatic event. The results provide positive impacts with respect to the proposed approaches. The grid, however, is sometimes subjected to multiple events at the same time. [27] [30] categorised quantitative resilience evaluation into simulation-based methods, the analytic methods, and the statistical analyses. Among them, the simulation-based method is most widely used because it can be easily combined with disaster scenarios and the disaster effect can be readily calculated [25]. [2] classified resilience evaluation methods into Monte Carlo simulations, contingency based, machine learning based and Bayesian network-based methods. [9] considered multi-stage resilience assessment, and the key problems of each stage can be revealed by splitting the resilience assessment into three elements: pre-disaster system resilience, during-disaster system endurance and post-disaster system repair capability.

Different quantitative resilience frameworks have so far been reported in literature by [6]–[9], [11], [13], [19], [21], [37], [41], [42], [45]–[47], [67], [75], [113]. These were compared and numerous conclusions or recommendations were drawn. Table 3 is also used in the analysis.

1. There was no standard framework. While some started with threat identification and / or characterization [6], [19], [37], [45], [46], others started by defining the resilience goals [7], [13]. Others begun by defining data requirements [9], [21], [42], [44], [47] as well as defining the resilience metrics [41].
2. There were limited studies in both qualitative and hybrid resilience assessment approaches. Most frameworks only consider quantitative resilience assessment.
3. There were limited studies in pre-event resilience assessment (preparedness). One framework demonstrated the need for planning resilience [47]. The planning resilience helps to identify weak or potential weak points and informs planning and operational decisions.
4. Cost – benefit analysis of the enhancement strategies has not been extensively studied. [44] demonstrated identification and prioritization of enhancement measures before cost-benefit analysis. Much as identification should precede cost-benefit analysis, prioritization would be ideal if it is based on the cost-benefit analysis. [21] recognized the need for cost-benefit analysis in the identification and implementation of enhancement measures.

5. Mono-hazard quantitative resilience assessment approach was considered. The grid is susceptible to multiple hazards. Enhancement measures for one hazard might lower the resilience of the grid to a different hazard.
6. The resilience frameworks depend on location because events were area specific. [13] demonstrated that resilience frameworks are not one size fits all methods.
7. Not all resilience studies resulted in resilience enhancement. Authors in [6], [9], [19], [41], [42], [44] indicated that some resilience studies aimed at establishing the resilience status of the power system.
8. Despite the diversities, the common stage in resilience studies was impact assessment which was in form of
    a. Vulnerability assessment of system's components [37]
    b. Component functionality assessment [46] e.g., transmission system functionality
    c. Expected system performance evaluation [19] e.g., expected energy to be served
    d. Determining the extent of system degradation [41]
    e. Establishing power system components outage [6]
    f. Assessing the following [21]
        i. Level of preparedness
        ii. How low system degrades
        iii. How fast system is restored after disruption
        iv. How system adapts to disturbance
    g. Determination of level of disruption [7]
    h. Situational analysis [44]
    i. Evaluation of affected resilience indicators [9], [42]

Figure 4 is a summary of the review of available resilience frameworks. Depending on various presentations, the resilience assessment took different approaches. Principally, the main activities in resilience studies are represented by numbers 1 to 5 in Figure 4. Approach 1 – 5 means that the authors started with threat identification followed by resilience assessment. Depending on resilience goals, some studies ended with resilience assessment [6], [13], [19], [37], [41], [44], [47] while others ended with resilience enhancement [7], [9], [21], [45], [46], [113]. The following approaches were noted: ***1-5*** [45], [46], ***1-2-5*** [19], ***2-1-5*** [41], ***4-5*** [21], [37], ***1-4-5*** [6], ***3-2-1-5*** [7], ***4-1-5*** [44], ***2-5*** [113], and ***4-2-5*** [9], [42].

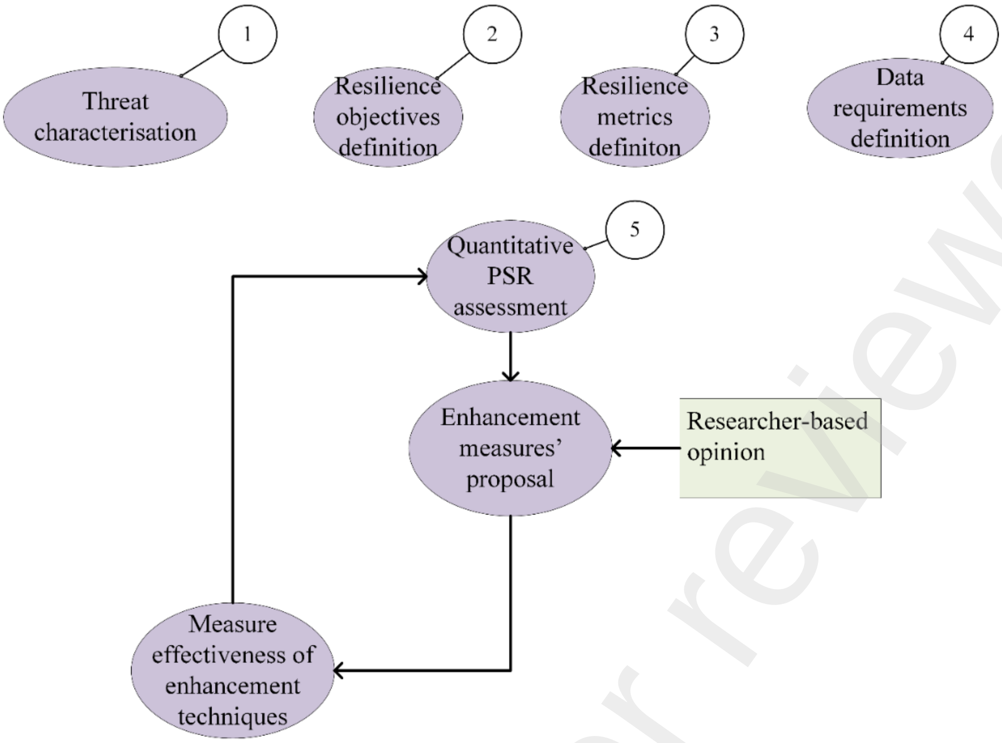

Figure 4. Summary of available reviewed resilience frameworks

It is clear that none of authors used all the steps of Figure 4, neither did they combine qualitative and quantitative evaluation. This is why a 9-Step comprehensive PSR assessment and enhancement framework shown in Figure 5 is proposed. This framework provides platform for mixed methods approach to power system resilience assessment and enhancement. The proposed framework informs long-term resilience planning in terms of both economic and technical viability of enhancement measures. It further provides for interdisciplinary enhancement measures through stakeholder engagement in identification of resilience improvement techniques. Stakeholder involvement in resilience improvement is key in acceptance and implementation of measures. This framework can be used by a variety of user groups, from researchers to industries or sectors. It may be used in resilience assessment and enhancement of other critical infrastructures, with or without modifications, depending on outcomes of implementation.

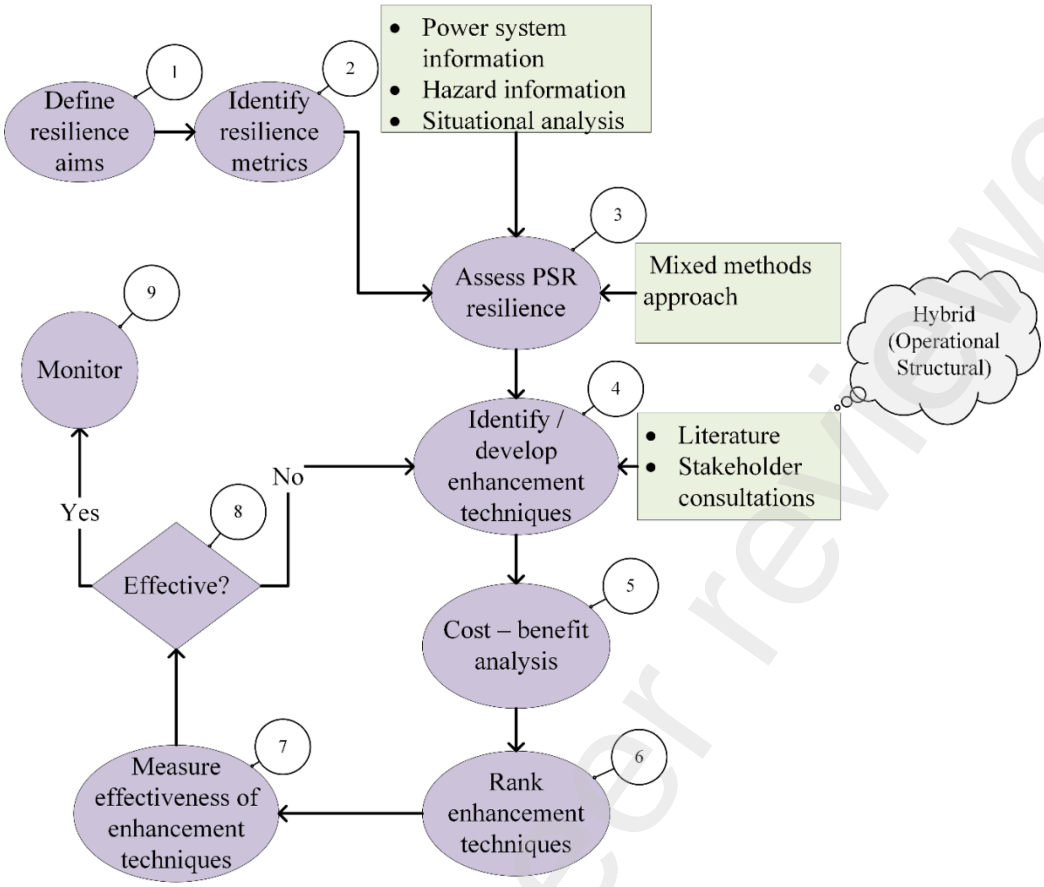

Figure 5. Proposed 9-Step comprehensive PSR assessment and enhancement framework

7.0 PSR Enhancement Strategies

Two purposes served by grid resilience enhancement strategies are 1) decreasing the magnitude of the immediate impact caused by an extreme weather event and 2) restoring the grid functionality to its normal state as rapidly as possible after the extreme weather event. The type of grid resilience assessment used determines the choice of enhancement strategies. Many researchers categorized grid enhancement into (structural) physical hardiness and (non-structural) operational capability [3], [5], [25], [75], [114], [50]. Structural enhancement is used to decrease the magnitude of the impact, and non-structural enhancement is applied to decrease the restoration time or increase grid functionality [11]. Thus, embracing both measures (''Hybrid enhancement'') might guarantee both impact and restoration time reduction. On the contrary, [29] grouped the resilience enhancement approaches into planning and operational methods, which can either be short or long term. The planning can be carried out by strengthening the system to a superior model. Operational methods, permit the operators of the system to access outage information within minutes of the disruption and take active actions. It was argued in [72] that underlying enhancement principles can be categorized into system executions; regional methods; community methods; national methods; methods highlighting the role of the valuation; methods emphasizing the notion of security and plea for risk super vision studies; and sectoral methods.

Prior studies have evaluated both structural (S) [3], [20], [49]–[53] and non-structural or operational (Op) [14], [16], [46], [54]–[60], [63] PSR enhancement techniques, separately. A detailed grid resilience enhancement review is presented by [105]. The review results suggested that none of the studies reflected hybrid enhancement strategies nor the cost-benefit analysis of enhancement measures as shown in Table 4, where S and Op stand for structural and operational, respectively. [20] introduced a resilience metric framework and methodology to match the cost-benefit of changes where the benefit of an improvement made to the system is assessed by the change in the adaptive resilience metric. [46] suggested that the ability of the power system to go back to its normal working state after suffering an attack from a hazard relies not only on the intrinsic features of a power system infrastructure but also on its operative efficacy. Thus, the rationale for the appropriate roadmap for improving PSR is to combine both structural and non-structural approaches to optimize the investment and to build a more resilient power system. strategies. The next section identifies the current gaps based on this study.

Table 4. Identifying types of resilience enhancement studied and consideration of cost – benefit analysis

Ref.	[3]	[14]	[16]	[20]	[46]	[49]	[50]	[51]	[52]	[53]	[51]	[54]	[55]	[56]	[57]	[58]	[59]	[60]
Enhancement class	S	Op	Op	S	Op	S	S	S	S	S	Op	Op	Op	Op	Op	Op	Op	Op
Consideration of cost-benefit analysis	-	-	-	✓	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-
Hybrid enhancement	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

8.0 Current gaps

8.1 PSR assessment and enhancement.

Prior studies have looked at different threats that incapacitate the power system. These were hurricane [20], [36], [62], windstorms [39], [52], [60], [122], typhoon [6], [47], [114], distinct forms of crises [19], physical attacks [14], absenteeism pandemics [123], high winds [40], [52], floods [51], earthquake [53], wildfire [124], and cyber-attacks [125] [57]. Studies combining two or more LPHI events such as typhoon and flood are yet to be conducted even though power systems may be subjected to multiple hazards. In the absence of multi-hazard assessment and enhancement, enhancement efforts for one hazard might be a threat to the resilience of the system to a different hazard. Therefore, it is essential to undertake research into the impacts of muti-hazard events.

8.2 CC, Electricity demand and PSR

Electricity demand is one of the power system components that affect the stability or resilience of the grid [99]. It should therefore be considered a potential threat to grid resilience. The implication of increased demand on the PSR in terms of transmission capacity cannot be overemphasized. Limited studies have been reported in literature in relation to the impact of demand on PSR under increasing CC. It is critical to consider demand increase in resilience studies because demand side measures are believed to have a superior capability of creating the overall energy system more efficient, flexible, and resilient at relatively low costs [126]. There are also limited studies in PSR regarding CC. Most CC studies present impacts of CC on electricity demand.

6.3 Resilience attributes

Desired properties of PSR metrics have been reported while some have been summarized in 5.1. However, the literature does not indicate if all the attributes of PSR or only a few are needed. According to [33], the attributes were assigned based on the nature of the scope and methodology used to build the metrics. While their assignment presents a better understanding when faced with how to choose a quantitative metric, it was felt that these should have been the classifications of quantitative resilience metrics. Irrespective of each category, for example, regardless of whether metrics are stochastic, dynamic, or cost based, they must have specific properties which must be met when selecting them. This calls for extensive research to construct a scientific conclusion.

6.4 PSR modeling, evaluation approaches and enhancement

Different authors have presented different power system modelling and evaluation approaches. [35] reviewed quantitative modelling and evaluation approaches. None of the studies indicate which of the evaluation approaches is most preferred or produces the most accurate results. In [19], simulation-based methods were indicated to be the most widely used. However, there was no indication if they were more accurate than others depending on circumstances. A deliberate study to establish this would be a welcome development. Further, there was a lack of evaluation approaches for qualitative PSR assessment. There were no qualitative evaluation frameworks nor qualitative PSR studies. Qualitative studies in resilience have been done by [117]–[120]. But none of these specifically studied the qualitative PSR, although [117] assessed common issues that create barriers to increased resilience and one of the cases it was a power industry. Qualitative resilience studies will help to identify strengths and weaknesses in terms of resilience [117]. Also, there was no standard framework for PSR assessment and evaluation. This brings challenges when selecting frameworks. Notably, none of the prior studies have considered hybrid resilience assessment nor cost benefit analysis of the enhancement measures.

9.0 Conclusions

This review used existing methods to answer the study questions. In summary, the concepts of PSR which include definitions, types and general considerations was covered. A standardized definition of PSR is yet to be constructed. Factors to be considered when constructing a standard PSR definition have been proposed, in addition to those in literature. Ability of the power system to perform all the resilience properties and maintain sustainable electricity supply regardless of extent, type, severity, and duration of event or potential event are key characteristics. Further, limitation of impact or loss and extent of preparation, anticipation, adaptation, resistance, response, absorption, degradation, and transformation should also be considered in defining power system resilience. In addition, the importance of rapid power system recovery and the definition of acceptable level of loss or impact are considered critical in defining power system resilience. Finally, the associated recovery costs and continued operation of the power system in damaged states need emphasis, in addition to the dynamic nature of resilience. The study also reviewed the threats to power systems which compromise their resilience. Included in the threats are the impacts of CC on PSR. The impacts of increasing CC were observed in power generation, delivery and consumption. Results revealed that changes in electricity demand patterns, which in turn affect resilience is one of the impacts. Climate change adaptation to enhance PSR can be in form of structures, capacity building, institutional improvement and effective operating procedures. Whilst reviewing PSR concepts, the criteria for selection of quantitative metrics were identified. The criteria depend on 1) the aim of the resilience study, 2) inherent uncertainty in the grid, 3) policy directives, 4) functional capabilities of the power system, 5) expected degree damage of the system, risk of system splitting and generation and transmission margins, 6) extreme event phases and critical infrastructure, 7) RT and class of systems and 8) type of data. This review further compared different RT and frameworks, identified the gaps in these and used them to propose a summarized climate change enhanced trapezoid and comprehensive resilience assessment and enhancement frameworks. In the frameworks is the first ever qualitative PSR assessment and enhancement framework. Even with extensive research in PSR, significant gaps still exist which form the basis for further research. Some gaps are 1) multi-hazard PSR assessment and enhancement, 2) impact of increasing demand and CC on PSR, 3) qualitative PSR assessment and enhancement and 4) cost-benefit analysis for enhancement measures. It is not known whether all listed attributes of PSR metrics are required or not. Notably, there is no standard framework for quantitative PSR assessment and enhancement. In further studies, the proposed approaches will be tested for effectiveness.

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Appendices

Appendix 1. Power system resilience review article search methodology. Adapted from [32]

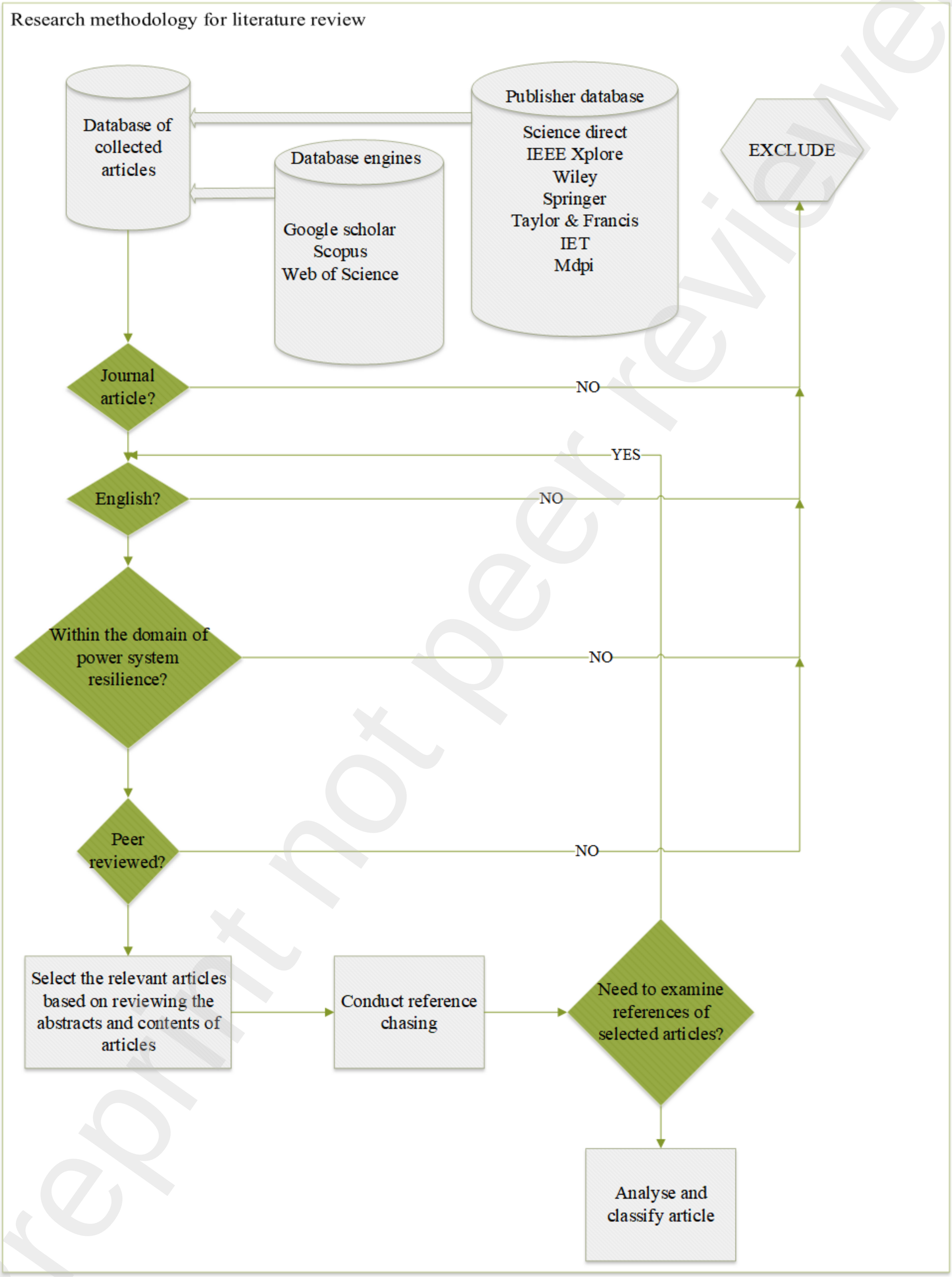

Figure A.1. Power system resilience review article search methodology. Adapted from [32]

Appendix 2. Comparative analysis of resilience trapezoids

Table A.1. Comparative analysis of resilience trapezoids

Ref.	**Name**	**Y-axis (measured quantity)**	**Number of stages, description, and characteristics**							**Initialisation of degradation state**	**Position of measured quantity after restoration**
			Stage / characteristic	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**		
[6], [34]	resilience curve, system status curve	power system status	Stage	normal state	resistive state	degraded state	restorative state	normal	-	delay	pre-event state
			Characteristic	-	-	-	-	-	-		
[13]	indicative scenarios & capacities of resilience	resilience level	Stage	status quo operation	absorption phase	adaptation phase	recovery phase	transformation phase	new normal	Immediately	reduced capacity / bouncing back / increased capacity
			Characteristic	prevention & anticipation	coping			capacity			
[17]	multi-phase resilience trapezoid	resilience indicator (%age)	Stage	pre disturbance resilience state	disturbance progress	post disturbance degraded state	restorative state	post restorative state	-	Immediately	pre-event state
			Characteristic	-	-	-	-	-	-		
[19]	illustrative process	system function (F(t))	Stage	pre disaster state	during disaster state	post disaster state	-		-	Immediately	pre-event state

			Characteristic	preparation / anticipation	resistance	response	recovery	-	-		
[35]	disturbance & impact assessment	performance level (%age)	Stage	recondition state	resist state	response state	recovery state	restorative state	-	Immediately	pre-event state
			Characteristic	robustness	brittleness / fragility			-	-		
[36]	performance curve	performance level (%age)	Stage	disaster prevention	damage propagation	assessment & recovery	-	-	-	Immediately	Pre-event status
			Characteristic	-	-	-	-	-	-		
[37]	resilience curve	resilience (unit)	Stage	resilient state	event progress	post event degraded state	restorative state	post restoration state	-	Immediately	Pre-event status
			Characteristic	robustness / resistance	resourcefulness/ redundancy / adaptive self organisation		recovery / response	robustness / resistance	infrastructure recovery		
[38]	performance & state transition	functionality (Q(t))	Stage	stable original state	system disruption	disrupted state	system recovery	stable recovered state	-	Immediately	reduced functionality
			Characteristic	reliability	vulnerability	recoverability		-	-		
[39]	resilience trapezoid	resilience level (Rt)	Stage	pre disturbance resilience state	disturbance progress	post disturbance degraded state	restorative state	post restorative state	-	Immediately	pre-event state
			Characteristic	prevention	correction	emergency coordination	restoration	adaptation	-		
[41]	linear approximation of system	performance indicator (Po)	Stage	-	-	-	-	-	-	Immediately	pre-event state
			Characteristic	avoidance	survival	recovery			-		

	performance										
[40]	resilience curve	resilience state (Rt)	Stage	normal	alert / emergency	in extremis	restorative state	normal	-	Immediately	pre-event state
			Characteristic	security	-	-	-	-	-		
[28]	illustrative process of power system performance changes	system performance	Stage	preparedness / primary operation mode state	resistance phase	response phase	recovery phase	ultimate operation mode	-	Immediately	reduced performance
			Characteristic	prevention & anticipation	coping			capacity			

Appendix 3. PSR definitions

TableA.2. PSR definitions

Ref.	Definition
[6]	‘‘ability of a power system to anticipate, absorb, resist, respond to and rapidly recover from a disruption, caused by a high-impact, low-probability event.’’
[6], [15], [20], [49], [62], [63]	‘‘ability of a power system to resist, respond, and recover from a catastrophic event,’’
[7]	‘‘ability to protect against and recover from any event that would significantly impact the grid.”
[10]	‘‘ability to maintain the electricity supply in the face of a high-impact, low probability disturbances, reducing the area of the RT”
[13]	Considers transformation of the original power system where system functionality is an improved version of the original system.
[16]	“Ability of an entity to anticipate, resist, absorb, respond to, adapt to and recover from a disturbance.”
[18]	“Ability of an entity to anticipate, resist, absorb, respond to, adapt to and recover from a disturbance”
[19]	‘‘anticipate possible disasters, adopt effective measures to decrease system components and load losses before and during disasters, and restore power supply quickly.’’
[35]	‘‘ability of the power system to withstand within an acceptable level and recover within acceptable time and cost.’’
[39]	‘‘ability of a power system to recover quickly following a disaster or, more generally, to the ability of anticipating extraordinary and high-impact, low-probability events, rapidly recovering from these disruptive events, and absorbing lessons for adapting its operation and structure to be better prepared for similar events in the future.’’
[41]	‘‘the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event."
[40]	‘‘ability to degrade gradually under increasing system stress and then to recover to its pre-disturbance secure state.’’
[49]	‘‘the ability of a system to prepare for, respond to and recover from natural and man-made disasters.’’
[62]	‘‘ability of a power system to resist, respond, and recover from a catastrophic event, and continue to operate in a disturbed state’’
[64]	“Ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.’’
[71]	‘‘ability of a system to anticipate and withstand external shocks, bounce back to its pre-shock state as quickly as possible and adapt to be better prepared to future catastrophic events.’’

[68]	‘‘the degree / extent to which the grid can withstand unexpected events without degradation in performance.’’
[65]	‘‘the ability to limit the extent, severity, and duration of system degradation following an extreme event’’
[66]	‘‘ability to withstand and recover from the high-impact low-probability events.’’
[69]	‘‘ability of this system to withstand disasters (low-frequency high-impact incidents) efficiently while ensuring the least possible interruption in the supply of electricity, sustain critical social services, and enabling a quick recovery and restoration to the normal operation state.”